

This article was downloaded by: [USDA Natl Agricultul Lib]

On: 28 May 2010

Access details: Access Details: [subscription number 917343524]

Publisher Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



## Communications in Soil Science and Plant Analysis

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713597241>

### Enzyme activities in Cerrado soils of Brazil

V. C. Baligar<sup>a</sup>; R. J. Wright<sup>b</sup>; N. K. Fageria<sup>c</sup>; G. V. E. Pitta<sup>d</sup>

<sup>a</sup> USDA-ARS, Beaver, WV <sup>b</sup> USDA-ARS, BARC-West, Beltsville, MD <sup>c</sup> NPAF-Embrapa, Goiania, GO, Brazil <sup>d</sup> CNPMS-Embrapa, Sete Lagoas, MG, Brazil

**To cite this Article** Baligar, V. C. , Wright, R. J. , Fageria, N. K. and Pitta, G. V. E.(1999) 'Enzyme activities in Cerrado soils of Brazil', Communications in Soil Science and Plant Analysis, 30: 9, 1551 — 1560

**To link to this Article:** DOI: 10.1080/00103629909370306

**URL:** <http://dx.doi.org/10.1080/00103629909370306>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

## Enzyme Activities in Cerrado Soils of Brazil

V. C. Baligar,<sup>a</sup> R. J. Wright,<sup>b</sup> N. K. Fageria,<sup>c</sup> and  
G. V. E. Pitta<sup>d</sup>

<sup>a</sup>USDA-ARS, P.O. Box 400, Beaver, WV 25813

<sup>b</sup>USDA-ARS, BARC-West, Beltsville, MD 20705

<sup>c</sup>CNPAF-Embrapa, Goiania, GO 74001-970, Brazil

<sup>d</sup>CNPMS-Embrapa, Sete Lagoas, MG 35701-970, Brazil

### ABSTRACT

Enzymes play an important role in cycling of organically bound nutrients in soils. Pyrophosphatase (PPi), acid phosphatase (AP), arylsulfatase (AS), urease (UR), and dehydrogenase (DH) activities were measured in air-dry samples from the top 15 cm of two dark red Latosols and four red-yellow Latosols from Cerrado regions of Minas Gerais (MG) and Goias (GO) Brazil. Relationships between enzyme activities and soil properties were examined. Among the six soils, the dark red Latosol from Sete Lagoas, MG, had the highest activities for AP, AS, and UR enzymes. The lowest activities for these enzymes were observed in a dark red Latosol from Uberaba, MG, and this soil also recorded the lowest DH activity. The red-yellow Latosol from Sete Lagoas, MG, had the highest PPi and DH. The activities, whereas a red-yellow Latosol from Felixlandia, MG, gave the lowest PPi activity. Activities of all enzymes were negatively correlated with sand and silt content and positively correlated with clay content. Overall, the enzyme activities were positively correlated with pH, organic carbon (C), Bray-P, and exchangeable potassium (K), calcium (Ca), and magnesium (Mg). Soil organic C appears to have the greatest effect on the level of enzyme activities in acid soils.

Each soil type has its own inherent levels of enzyme activities. Knowledge of relationships between enzyme activities and soil properties could be useful in development of sound fertilizer practices for Cerrado soils.

## INTRODUCTION

Enzymes in soil play a key role as catalysts of biochemical reactions and, thereby, mediate the transformation of organically bound nutrients into inorganic plant-available forms (Skujins, 1976; Speir and Ross, 1978). Hydrolase enzymes such as acid phosphatase (AP), arylsulfatase (AS), and urease (UR) have been studied in various types of soils and ecosystems of the world, and the levels of their activities are known to be related to soil physical and chemical properties (Baligar et al., 1988a, 1988b; Baligar and Wright, 1991; Bremner and Mulvaney, 1978; Skujins, 1976; Speir and Ross, 1978). These studies report that enzyme activities are directly related to soil organic C, but consistent relationships with soil texture, pH, exchangeable cations, and anions have not been reported (Bremner and Mulvaney, 1978; Skujins, 1976; Speir and Ross, 1978).

About 205 million ha of land area in Central Brazil is in Cerrado vegetation, and soils in this region are predominantly acidic and infertile. In addition to acid soil toxicity, deficiencies of phosphorus (P) and nitrogen (N) are major constraints for crop growth. Fixation of inorganic P by soil constituents has reduced the efficiency of added P fertilizers. Condensed fertilizer, high in polyphosphate and pyrophosphate, may slow the rate of ortho-P fixation. The inorganic pyrophosphatase (PPi) enzyme catalyzes the hydrolysis of pyrophosphate to orthophosphate. Acid-phosphatase is predominant in acid soil and plays a major role in the mineralization of organically bound P (Speir and Ross, 1978; Stevenson, 1986; Tabatabai, 1982). Arylsulfatase (AS) enzyme is probably responsible for mineralization of organic S (esters) into inorganic S. The AS has been detected in a range of soils (Baligar et al., 1988a; Baligar and Wright, 1991; Cooper, 1972; Speir, 1977; Tabatabai and Bremner, 1970). Dehydrogenase enzymes play a significant role in the biological oxidation of soil organic matter.

In recent years, urea has become a major source of N in the world. The efficient use of urea in acid soils is partially dependent upon urease activities. Low urease activity causes urea fertilizer loss due to leaching, and high urease activity may result in excess hydrolysis and lead to ammonia loss by volatilization.

The objectives of the present study were to: (1) assess the magnitude of enzyme activities in six acid soils from the Cerrado Region of Brazil, and (2) relate enzyme activities to selected physical and chemical properties of these soils.

## MATERIALS AND METHODS

### Soils

Six major soils from the Cerrado Region of Minas Gerais (MG) and Goias (GO) states of Brazil were selected for the study. Three of the soils (S1, S3, S4)

were classified as typic Haplorthox, and the remaining were typic Haplustox, (S2); typic Quartzipsamment (S5) and cambic Haplorthox (S6). The top 15-cm layer of each soil group was sampled from noncultivated areas, passed through a 2-mm sieve, air dried, and stored in plastic bags at room temperature prior to determination of enzyme activities. Selected physical and chemical properties are given in Table 1.

### Soil Analysis

Soils were analyzed for pH in a soil suspension using a soil:H<sub>2</sub>O ratio of 1:1. Aluminum (Al), Ca, and Mg were extracted by 1 M KCl. Aluminum was determined by titration with NaOH, and Ca and Mg by atomic absorption spectrophotometry. Potassium and P were extracted by the Mehlich 1 method (0.05 M HCl+0.0125 M H<sub>2</sub>SO<sub>4</sub>). Phosphorus was determined colorimetrically by using a phospho-molybdo blue color method. Potassium was measured in the extract by flame photometry. Total C was determined using a Leco Model 600 CHN analyzer (Leco Corp., St. Joseph, MI<sup>1</sup>). Organic sulfur (S) was computed by taking the difference between total S, determined by a Leco SC132 analyzer, and extractable S measured by the Bray method (0.025 M HCl+0.03 M NH<sub>4</sub>F). Particle size distribution of the soil samples was determined by the pipette method.

### Enzyme Assay

Pyrophosphatase, acid phosphatase, arylsulfatase, and urease activities were assayed according to the methods suggested by Tabatabai (1982). A Technicon Auto Analyzer II was used to determine ammonium released in urease activity. Dehydrogenase was assayed by the method of Casida et al. (1964) and Tabatabai (1982). Duncan's Multiple Range Test was used to evaluate statistical significant differences in each enzyme activity among six soils. Linear correlation coefficient analysis was used to relate enzyme activities to soil physical and chemical properties (SAS, 1998).

## RESULTS AND DISCUSSION

### Pyrophosphatase

Pyrophosphatase (PPi) activities in these soils ranged from 48 to 138 µg ortho P-released/g soil/5 h (Table 2). The red yellow Latosol (S2) from Sete Lagoas, MG, recorded the highest PPi activities. The PPi activities of Cerrado soils were comparable to activities observed in subsurface acid soils of the Appalachian Region (Baligar et al., 1991b) and other soils (Parent et al., 1985; Tabatabai and

<sup>1</sup>Mention of company or commercial products does not imply recommendation or endorsement by the USDA over others not mentioned.

TABLE 1. Physical and chemical properties of soils used.

Sand	Silt	Clay	Total C	P	Sulfur			Exchangeable				pH
					Total	Ext.	Organic	K	Ca	Mg	Al	1:1 Soil:H <sub>2</sub> O
-----g kg <sup>-1</sup> -----				μg g <sup>-1</sup>	-----μg g <sup>-1</sup> -----			-----cmol kg <sup>-1</sup> -----				
<u>S1 = Sete Lagoas, MG</u>												
110	170	720	39.5	2	186.5	21.1	162.4	0.13	0.67	0.11	1.75	4.9
<u>S2 = Sete Lagoas, MG</u>												
110	170	720	26.4	6	141.0	31.4	109.6	0.33	2.85	0.84	0.40	5.3
<u>S3 = Felixlandia, MG</u>												
320	230	450	17.4	2	258.0	30.3	277.7	0.26	0.19	0.07	1.35	4.6
<u>S4 = Patrocínio, MG</u>												
140	230	630	26.1	1	108.5	39.1	69.5	0.15	0.19	0.08	0.55	4.9
<u>S5 = Uberaba, MG</u>												
720	100	180	7.3	1	41.9	26.1	15.9	0.09	0.06	0.02	0.40	4.8
<u>S6 = Goiânia, GO</u>												
450	190	360	16.8	1	60.9	23.9	24.8	0.17	0.32	0.12	0.25	5.2

TABLE 2. Enzyme activities in Brazilian soils.

Soils	PPi <sup>a</sup>	AP <sup>b</sup>	AS <sup>c</sup>	UR <sup>d</sup>	DH <sup>e</sup>
S1	68 b <sup>f</sup>	289 a	107 a	65 a	26 b
S2	138 a	193 c	74 b	43 b	131 a
S3	48 b	129 c	9 de	5 d	10 cd
S4	52 b	217 b	25 c	12 c	10 cd
S5	50 b	55 f	4 e	8 cd	1 d
S6	80 b	152 d	14 d	48 b	18 bc
Mean	73	173	39	30	33
LSD 0.05	35	15	9	6	10

<sup>a</sup>PPi=pyrophosphatase µg ortho-P released/g soil/5 h.

<sup>b</sup>AP=acid phosphatase µg p-nitrophenol released/g soil/h.

<sup>c</sup>AS=arylsulfatase µg p-nitrophenol released/g soil/h.

<sup>d</sup>UR=urease µg of NH<sub>4</sub>-N released/g soil/2 h.

<sup>e</sup>DH=dehydrogenase µg TPF produced/g soil/24 h.

<sup>f</sup>Means in each column not followed by the same letter differ at the 0.05 levels of probability by DMR test.

Dick, 1979). Higher PPi activities are invariably related to high organic C content of soils. In the current study, PPi activity was positively related to C content of soils (Table 3). Baligar et al. (1991b) have reported a highly significant positive relationship between PPi activities and organic C content of surface horizons of the acid Appalachian soils. Tabatabai and Dick (1979) reported that soils with pH <7.0 gave a high degree of correlation ( $r=0.90^{**}$ ) between PPi activity and organic C.

No significant relationships were observed between PPi activities and clay, silt, and sand content of soils. Tabatabai and Dick (1979) reported a positive relationship between PPi activity and clay content for Iowa soils. A positive and significant relationship between PPi activity and soil pH was observed in the current study. Baligar et al. (1991b), in Appalachian soils, and Tabatabai and Dick (1979), in Iowa soils, have reported negative relationships between PPi activity and soil pH.

Positive relationships were observed between PPi activities and soil content of Bray-1P, exchangeable K, Ca, and Mg. However, the relations were only significant for Bray-1P, Ca, and Mg. Baligar et al. (1991b) have reported positive relationships between exchangeable bases such as K, Ca, and Mg.

### Acid Phosphatase

The level of acid phosphatase (AP) activities observed in Cerrado soils was comparable to AP activities observed on other types of soils (Table 2) (Baligar et

TABLE 3. Correlation coefficient (r) between soil physical and chemical properties and various enzyme activities in six soils from Brazilian Cerrado.

Soil properties	Pyro-phosphatase	Acid-phosphatase	Aryl-sulfatase	Urease	Dehydrogenase
<b>Physical</b>					
Clay	0.49NS	0.90*	0.81NS	0.51NS	0.57NS
Silt	-0.12NS	0.41NS	-0.07NS	-0.12NS	-0.07NS
Coarse sand	-0.21NS	-0.44NS	-0.25NS	-0.18NS	-0.27NS
Fine sand	-0.42NS	-0.90*	-0.76NS	-0.45NS	-0.50NS
<b>Chemical</b>					
pH-H <sub>2</sub> O	0.86*	0.26NS	0.35NS	0.62NS	0.71NS
C	0.28NS	0.99**	0.90*	0.68NS	0.32NS
Bray-P	0.89*	0.22NS	0.53NS	0.30NS	0.97**
Total-S	-0.09NS	0.30NS	0.25NS	-0.06NS	0.06NS
Organic-S	-0.12NS	0.25NS	0.22NS	-0.09NS	0.04NS
Extract-S	-0.01NS	0.02NS	-0.30NS	-0.61NS	0.13NS
Exch.* K	0.69NS	0.09NS	0.17NS	0.05NS	0.77NS
Exch. Ca	0.96**	0.29NS	0.57NS	0.42NS	0.99**
Exch. Mg	0.96**	0.20NS	0.46NS	0.33NS	0.99**

\*Exch.=exchangeable.

\*, \*\*Significant at 0.05 and 0.01 levels of probability, respectively.

NS=not significant.

al., 1988b; Skujins, 1976; Speir and Ross, 1978). Dark red Latosol from Sete Lagoas, MG (S1), recorded the highest and dark red Latosol from Uberaba, MG (S5), recorded the lowest AP activities. The AP activities gave positive significant relations with clay content and negative significant relation with fine sand content (Table 3). Baligar et al. (1988b) did not find any significant relations between AP activities and sand, silt, and clay content of 14 hill-land acid soils. In the current study, no significant relation was observed between AP activity and soil pH. Baligar et al. (1988b) reported a negative relationship between AP activity and soil pH in acid soils (pH 3.3 to 5.1). A significant positive relationship between AP activity and soil C was found. Such a relationship was well documented in various other types of soils (Baligar et al., 1988b; Skujins, 1976; Speir and Ross, 1978). The AP activities were positively related to Bray-1P, forms of S and exchangeable K, Mg, and Ca. Linear, inverse, and no relationships between AP activities and inorganic P content have been reported by Baligar et al. (1988b); Halsted (1964); and Speir and Ross (1978). The P levels in the six soils used were low enough that AP activities were induced, not repressed by inorganic P.

# Arylsulfatase

A dark red Latosol from Sete Lagoas, MG (S1), recorded the highest, and the dark red Latosol from Uberaba, MG (S5), recorded the lowest arylsulfatase (AS) activity (Table 2). The levels of AS activities observed in the Cerrado soils were comparable to AS activities reported in other types of soils (Baligar and Wright, 1991; Cooper, 1972; Speir, 1977, 1984; Tabatabai and Bremner, 1970). The AS activities were positively correlated with clay content and negatively correlated with sand and silt content of soils (Table 3). Tabatabai and Bremner (1970) found no significant relation between AS activities and clay and sand content of Iowa soils.

The AS activities were positively correlated with soil pH of Cerrado soils. Positive and negative relationships between AS activities and soil pH have been reported by Baligar and Wright (1991), Frankenberger and Dick (1983), Speir (1977, 1984), and Tabatabai and Bremner (1970).

The positive correlation between AS activity and soil organic C was statistically significant (Table 3). A similar relationship has been reported for other types of soils by Baligar and Wright (1991), Cooper (1972), Speir (1977, 1984), and Tabatabai and Bremner (1970). Such a correlation suggested the possibility for AS to be present as a humic-protein complex that protected it from microbial decomposition (Stevenson, 1994; Tan, 1993). Positive relations were also observed between AS activities and inorganic P, organic S, and exchangeable K, Ca, and Mg of the Cerrado soils. Speir (1984) has reported positive and negative relationships between AS activities and extractable inorganic P in Cook Island and Tongan soils. Baligar and Wright (1991) have reported positive significant and nonsignificant relationships between AS activity and exchangeable bases in hill-land acid soils.

# Urease

The dark red Latosol from Sete Lagoas, MG (S1), recorded the highest, and the red-yellow Latosol from Felixlandia, MG (S3), recorded the lowest urease (UR) activity (Table 2). The level of UR activities observed is comparable to UR activities in various types of soils as reported by Baligar et al. (1991a), Dalal (1975), and Panchoy and Rice (1973) which were found to be correlated to soil physical and chemical properties (Dalal, 1975; O Toole et al., 1985; Speir, 1984; Zantua et al., 1977). The UR activities were positively correlated to clay content and negatively correlated to sand and silt content (Table 3). A positive relationship between UR activity and soil clay content (Baligar et al., 1991a; Dalal, 1975; Frankenberger and Dick, 1983; Zantua et al., 1977) and a negative relationship between UR activity and sand content (Baligar et al., 1991a; Frankenberger and Dick, 1983) has been reported.

The relationship between UR activity and soil pH was positive (Table 3). However, negative (Baligar et al., 1991a; Frankenberger and Dick, 1983; Speir,



1984) and positive (Speir, 1984) relationships between UR and pH have been reported in various types of soils.

A positive relation between UR activity and soil C was observed in the Cerrado soils. A high degree of correlation (Baligar et al., 1991a; Dalal, 1975; Speir, 1984; Zantua et al., 1977) and no relationship (Pancholy and Rice, 1973) between UR activities and soil organic C have been reported. The UR activities in the current study were positively related to inorganic P and negatively related to organic and extractable S. Speir (1984) has reported positive and negative relationships between UR and extractable P and S in Cook Island and Tongan soils. The UR activities were positively related to exchangeable K, Ca, and Mg. Similar observations have been reported by Baligar et al. (1991a) in acid, hill-land soils of the Appalachian region of the United States.

### Dehydrogenase

The red-yellow Latosol from Sete Lagoas, MG (S2), had the highest, and dark red Latosol from Uberaba, MG (S5), had the lowest dehydrogenase (DH) activity (Table 2). The levels of DH activities in Cerrado soils were comparable to DH activities reported for acid subsoil horizons of the Appalachian region in the United States by (Baligar et al., 1991c). Wide ranges of DH activities have been reported in various types of soils by Baligar et al. (1991c), Frankenberger and Dick (1983), and Pancholy and Rice (1973).

The DH activity was positively related to clay and negatively related to the silt and sand content of the soil (Table 3). Positive and negative relationships between DH activity and clay, silt, and sand content of soil have been reported (Baligar et al., 1991c; Frankenberger and Dick, 1983). The DH activity in the Cerrado soils was positively related to soil pH, whereas positive (Baligar et al., 1991c), negative (Baligar et al., 1991c; Frankenberger and Dick, 1983), and no relationship (Pancholy and Rice, 1973) have been reported in the literature. In the current study, DH activity was positively related with organic C, which was in agreement with that reported by Baligar et al. (1991c), though negative and no relationship have also been reported (Pancholy and Rice, 1973; Baligar et al., 1991c). The DH activities were correlated significantly with Bray-1P and exchangeable Ca and Mg which was supported by Baligar et al. (1991c), though the latter authors reported positive and negative correlation for DH activities and different forms of P and S.

### ACKNOWLEDGMENTS

We thank M.D. Smedley and H.R. da Silveira for their excellent technical assistance and C.A. Vasconcellos and B.C. Avelar for their assistance in collection and identification of the soils. We thank Drs. I.P. Oliveira, L.G. Dutra, and an anonymous reviewer, for their excellent review of the manuscript.

# REFERENCES

- Baligar, V.C. and R.J. Wright. 1991. Enzyme activities in Appalachian soils. 1. Arylsulfatase. *Commun. Soil Sci. Plant Anal.* 22:305-314.
- Baligar, V.C., T.E. Staley, and R.J. Wright. 1991a. Enzyme activities in Appalachian soils. 2. Urease. *Commun. Soil Sci. Plant Anal.* 22:315-322.
- Baligar, V.C., R.J. Wright, and M.D. Smedley. 1988a. Enzyme activities in hill-land soils of the Appalachian Region. *Commun. Soil Sci. Plant Anal.* 19:367-384.
- Baligar, V.C., R.J. Wright, and M.D. Smedley. 1988b. Acid phosphatase activity in soils of the Appalachian Region. *Soil Sci. Soc. Am. J.* 52:1612-1616.
- Baligar, V.C., R.J. Wright, and M.D. Smedley. 1991b. Enzyme activities in Appalachian soils. 3. Pyrophosphatase. *Commun. Soil Sci. Plant Anal.* 22:1537-1545.
- Baligar, V.C., R.J. Wright, and M.D. Smedley. 1991c. Enzyme activities in Appalachian soils. 4. Dehydrogenase. *Commun. Soil Sci. Plant Anal.* 22:1797-1804.
- Bremner, J.M. and R.L. Mulvaney. 1978. Urease activity in soils. pp. 149-196. In: R.G. Burns (ed.), *Soil Enzymes*. Academic Press, Inc., New York, NY.
- Casida, Jr., L.E., D.A. Klein, and T. Santoro. 1964. Soil dehydrogenase activity. *Soil Sci.* 98:371-376.
- Cooper, P.J.M. 1972. Arylsulfatase activity in northern Nigerian soils. *Soil Biol. Biochem.* 4:333-337.
- Dalal, R.C. 1975. Urease activity in some Trinidad soils. *Soil Biol. Biochem.* 7:5-8.
- Frankenberger, Jr., W.T. and W.A. Dick. 1983. Relationships between enzyme activities and microbial growth and activity indices in soil. *Soil Sci. Soc. Am. J.* 47:945-951.
- Halsted, R.L. 1964. Phosphatase activity of soils as influenced by lime and other treatments. *Canadian J. Soil Sci.* 44:137-144.
- O'Toole, P., M.A. Morgan, and S.J. McGarry. 1985. A comparative study of urease in pasture and tillage soils. *Commun. Soil Sci. Plant Anal.* 16:759-773.
- Pancholy, S.K. and E.L. Rice. 1973. Soil enzymes in relation to old field succession: Amylase, cellulase, invertase, dehydrogenase, and urease. *Soil Sci. Soc. Am. Proc.* 37:47-50.
- Parent, L.E., A.F. MacKenzie, and Y. Perron. 1985. Influence of four levels of pyrophosphatase activity on the rate of pyrophosphate hydrolysis in organic soils. *Commun. Soil Sci. Plant Anal.* 16:1095-1105.

- SAS. 1998. SAS/STAT User's Guide. Version 6.03 ed. Statistical Analysis System Institute, Cary, NC.
- Skujins, J. 1976. Extracellular enzymes in soil. *CRC Crit. Rev. Microbiol.* 4:383-421.
- Speir, T.W. 1977. Studies on a climosequence of soils in tussock grasslands. II. Urease, phosphatase, and sulfatase activities of top soils and their relationships with other properties including plant available sulphur. *New Zealand J. Sci.* 20:159-166.
- Speir, T.W. 1984. Urease, phosphatase, and sulfatase activities of Cook Island and Tongan soils. *New Zealand J. Sci.* 27:73-79.
- Speir, T.W. and D.J. Ross. 1978. Soil phosphatase and sulphatase. pp. 197-250. In: R.G. Burns (ed.), *Soil Enzymes*. Academic Press, New York, NY.
- Stevenson, F.J. 1986. Cycles of soil-carbon, nitrogen, phosphorus, sulfur, micronutrients. Wiley InterScience, New York, NY.
- Stevenson, F.J. 1994. Humus chemistry: Genesis, composition, reactions. John Wiley and Sons, New York, NY.
- Tabatabai, M.A. 1982. Soil enzymes. pp. 903-947. In: A.L. Page, R.H. Miller, and D.R. Keeney (eds.), *Methods of Soil Analysis. Part 2*. American Society of Agronomy, Madison, WI.
- Tabatabai, M.A. and J.M. Bremner. 1970. Factors affecting soil arylsulfatase activity. *Soil Sci. Soc. Am. Proc.* 34:427-429.
- Tabatabai, M.A. and W.A. Dick. 1979. Distribution and stability of pyrophosphatase in soils. *Soil Biol. Biochem.* 1:655-659.
- Tan, K. M. 1993. Principles of Soil Chemistry. Marcel Dekker, Inc., New York, NY.
- Zantua, M.I., L.C. Dumenil, and J.M. Bremner. 1977. Relationships between soil urease activity and other soil properties. *Soil Sci. Soc. Am. J.* 41:350-352.